

Observations of Six Glitches in PSR B1737–30

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ABSTRACT

Six glitches have been recently observed in the rotational frequency of the young pulsar PSR B1737–30 (J1740–3015) using the 25-m Nanshan telescope of Urumqi Observatory. With a total of 20 glitches in 20 years, it is one of the most frequently glitching pulsars of the ~ 1750 known pulsars. Glitch amplitudes are very variable with fractional increases in rotation rate ranging from 10^{-9} to 10^{-6} . Inter-glitch intervals are also very variable, but no relationship is observed between interval and the size of the preceding glitch. There is a persistent increase in $|\dot{\nu}|$, opposite in sign to that expected from slowdown with a positive braking index, which may result from changes in the effective magnetic dipole moment of the star during the glitch.

Key words: stars: neutron – pulsars: individual: PSR B1737–30

1 INTRODUCTION

Glitches in pulsars are rare and extraordinary events. The study of such glitches and their post-glitch recoveries can give an insight into the interior of neutron stars, the physics of ultradense matter and provide limits on the equation of state (Pines 1991; Alpar et al. 1993; Franco et al. 2000). Pulsar glitches are usually detected from long-term and frequent timing observations. The number of observed glitches has increased dramatically in the past few years, which probably is due to both the increased continuous observations of active pulsars and a large number of new young pulsars detected by the pulsar surveys (e.g., the Parkes surveys, see Kramer et al. 2003) over the last decade.

Glitches are characterized as sudden increases in the rotation frequency $\nu = 1/P$ (where P is the pulsar period), often followed by an interval of approximately exponential recovery or relaxation back towards the pre-glitch frequency. The post-glitch relaxation can have timescale of days to years. Frequency jumps with magnitudes $\Delta\nu/\nu \sim 10^{-6}$ are recognized as “giant” glitches, and have been observed mostly in pulsars with characteristic ages $\tau_c = P/(2\dot{P}) \sim 10^4$ yr, such as PSRs B0833–45 (the Vela pulsar), B1046–58 and B1338–62 (Wang et al. 2000). Giant glitches have not been observed in the youngest radio pulsars, such as PSR B0531+21 (the Crab pulsar) and

PSR B1509–58. Detected glitches are generally of magnitude $10^{-9} < \Delta\nu/\nu < 10^{-6}$, and the relative increment in slow-down rate $\Delta\dot{\nu}/\dot{\nu}$ is in the range 10^{-3} to 10^{-2} . Very small glitches with $\Delta\nu/\nu < 10^{-9}$ are difficult to distinguish from timing noise in young pulsars (Hobbs et al. 2002). Of the 1750 known pulsars, about 170 glitches in 54 pulsars have been observed so far¹. Half of the published glitches have fractional amplitudes $\Delta\nu/\nu \sim 10^{-8}$. Most glitches detected in the Vela pulsar are giant glitches, and the largest glitch, with $\Delta\nu/\nu \approx 16 \times 10^{-6}$, was observed in PSR J1806–2125 (Hobbs et al. 2002). About 60% of the 54 glitching pulsars have glitched only once, and 16% have glitched twice. Observations with Rossi X-ray Timing Explorer (RXTE) have revealed that PSR J0537–6910, the 16-ms pulsar associated with the supernova remnant N157B in the Large Magellanic Cloud, is the most frequently glitching known pulsar with 23 glitches detected in seven years of monitoring (Middleditch et al. 2006). Most of the glitches have $\Delta\nu/\nu$ of a few $\times 10^{-7}$ and, interestingly, a strong correlation is observed between the amplitude of a glitch and the time to the next one. Furthermore, despite the usual post-glitch recovery (decrease) in $|\dot{\nu}|$, a persistent long-term increase in this parameter is observed, corresponding to a negative braking index $n = \nu\ddot{\nu}/\dot{\nu}^2 \sim -1.5$. This increase is

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¹ See <http://www.atnf.csiro.au/research/pulsar/psrcat/> and Manchester et al. (2005)

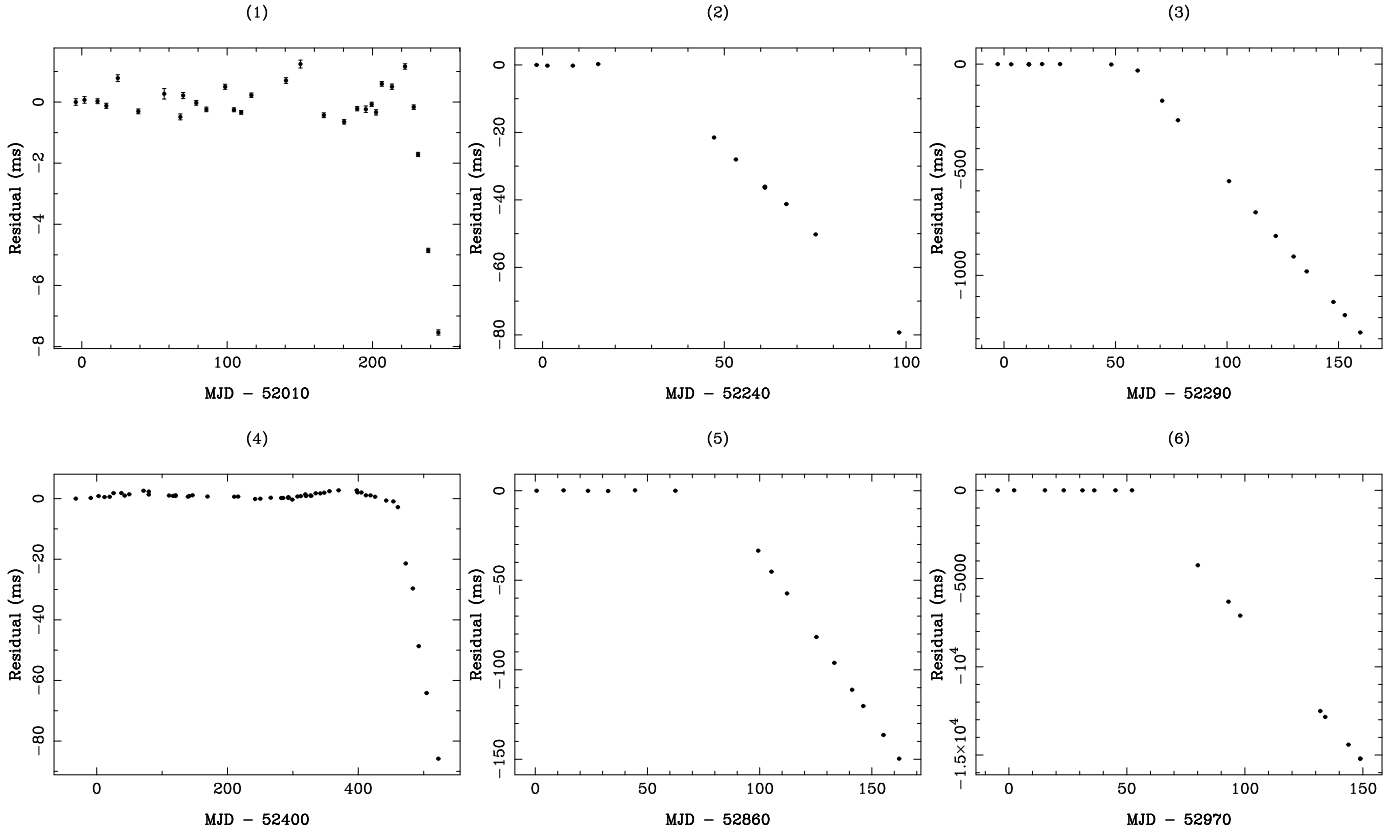


Figure 1. Timing residuals relative to the pre-glitch timing model for six glitches in the rotation history of PSR B1737–30. Residuals are defined in the sense of observed arrival time minus predicted arrival time.

most probably related to changes on or in the neutron star that result from the glitch activity.

In this paper we report on six recent glitches detected in the period of PSR B1737–30 and discuss the implications of these results. PSR B1737–30 is a young radio pulsar with a characteristic age of 2.06×10^4 yr which glitches frequently, with 20 glitches of all sizes ranging from “small” to “giant” ($\Delta\nu/\nu \sim 10^{-9}$ to 10^{-6}) observed since its discovery in 1986 (McKenna & Lyne 1990; Shemar & Lyne 1996; Krawczyk et al. 2003, this paper). As for PSR J0537–6910, there appears to be a cumulative shift in the spin-down rate of PSR B1737–30 resulting from its frequent glitches, which most likely accounts for its long-term braking index of $n = -4 \pm 2$ (Urama 2002).

2 OBSERVATIONS AND ANALYSIS

The timing observations of PSR B1737–30 using the 25-m Nanshan radio telescope of Urumqi Observatory started in 2000 January using a room-temperature dual-channel receiver. From 2002 July a dual-channel cryogenic receiver system sensitive to two orthogonal polarizations was used at a central observing frequency of 1540 MHz. Two polarizations, each of bandwidth 320 MHz, are fed to a filterbank consisting of 2×128 channels of width 2.5 MHz. The data are digitized to one-bit precision with a sampling interval of 1 ms. Time is provided by a hydrogen maser clock calibrated using the Global Positioning System. Observations times for PSR B1737–30 were generally 16 min with the room-temperature

receiver before 2002 July and 4 min with the cryogenic receiver after that date.

The data are dedispersed with off-line programs to remove the effects of interstellar dispersion, and then folded at the pulsar’s nominal topocentric period with four sub-integrations per observation. The pulse profiles obtained by summing an observation were cross-correlated with a high signal-to-noise template of the pulsar profile to produce accurate pulse topocentric times of arrival (TOAs), which are then processed with the standard timing program TEMPO² to convert them to barycentric arrival times at infinite frequency. The TOAs refer to the peak of the main pulse. The Jet Propulsion Laboratory ephemeris DE405 is used to correct the TOAs to the Solar system barycenter. The folded profiles are stored on disk for subsequent processing and analysis. Timing observations are usually made approximately three times per month and the glitching pulsars are observed more frequently.

We use the corrected barycentric TOAs to determine the basic parameters of the pulsar. The basic timing model gives the predicted rotational pulse phase $\phi_m(t)$, as a function of time, t :

$$\phi_m(t) = \phi_0 + \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}_0(t - t_0)^2 + \frac{1}{6}\ddot{\nu}_0(t - t_0)^3. \quad (1)$$

Timing irregularities appear as phase residuals ($\phi - \phi_m$), which are usually divided by ν to place them in time units.

² see <http://www.atnf.csiro.au/research/pulsar/tempo/>

For a glitching pulsar the residuals suddenly develop a negative slope at the time of the glitch as illustrated in Fig. 1. The frequency perturbation due to the glitch can usually be described by:

$$\Delta\nu(t) = \Delta\nu_p + \Delta\dot{\nu}_p t + \Delta\nu_d \exp(-t/\tau_d), \quad (2)$$

where $\Delta\nu = \nu - \nu_0$ is the change in pulse frequency relative to the pre-glitch model, $\Delta\nu_p$ and $\Delta\dot{\nu}_p$ are the permanent changes in frequency and frequency derivative respectively and $\Delta\nu_d$ is the amplitude of the exponential recovery with a decay time constant of τ_d . The total frequency jump at the time of the glitch $\Delta\nu_g = \Delta\nu_p + \Delta\nu_d$ and the degree of recovery is often described by the parameter $Q = \Delta\nu_d/\Delta\nu_g$. Because of the decaying component, the instantaneous change in $\dot{\nu}$ at the glitch differs from $\Delta\dot{\nu}_p$:

$$\Delta\dot{\nu}_g = \Delta\dot{\nu}_p - Q\Delta\nu_g/\tau_d. \quad (3)$$

The glitch model of Equation 2 describes the post-glitch behaviour fairly well for most glitches (Shemar & Lyne 1996; Wang et al. 2000).

3 RESULTS

Six glitches have been observed in the period of PSR B1737–30 over the seven-year monitoring period from 2000 January 6 (MJD 51549) to 2006 December 25 (MJD 54094). The rotation history of these glitches with respect to pre-glitch timing models are shown in Fig. 1. No glitches have been observed since 2004 February, i.e., for nearly three years. Tables 1 and 2 give the main parameters of the six glitches. Uncertainties are parentheses and refer to the last quoted digit. Glitch parameters have been determined by fitting Equation 2 to the timing data around each glitch. For the smaller glitches, the glitch epoch is determined unambiguously by the requirement of pulse phase continuity. The last large glitch, the epoch is ambiguous and is given as the mean of the dates of the last pre-glitch and the first post-glitch observations. Except for the largest glitch, the magnitudes of these glitches are comparable to those observed from Crab pulsar ($\sim 10^{-8}$), but generally 2–3 orders smaller than the typical glitch of the Vela pulsar ($\Delta\nu/\nu \sim 10^{-6}$). No changes associated with the glitches in the pulse shape or flux density have been observed.

Fig. 2 shows the time-evolution of the residual frequency ($\Delta\nu$) and the frequency first derivative ($\dot{\nu}$) over a 2500-d period. The six glitches are clustered in two groups of three. The first observed glitch, at epoch MJD 52237 (2001 November 11, glitch 1 in Fig. 1) is very small, with a fractional change in the rotation rate $\Delta\nu_g/\nu \sim 5 \times 10^{-9}$. A relatively large glitch ($\Delta\nu_g/\nu \sim 1.52 \times 10^{-7}$) occurred at epoch MJD 52347.66 (2002 March 14, glitch 3 in Fig. 1), the amplitude of which is similar to a typical glitch of PSR B1758–23; PSRs B1737–30 and B1758–23 have similar properties — age, period, period derivative and spin-down energy loss rate. The relaxation after this glitch is adequately modelled by an exponential decay of time scale ~ 50 d with $Q \sim 0.1$. The largest glitch so far observed in this pulsar with $\Delta\nu/\nu = 1.85 \times 10^{-6}$ occurred on MJD 53036 \pm 13 (2004 February 1, glitch 6 in Fig. 1). This is a Vela-type glitch. Fitting glitch parameters to a relatively short (200

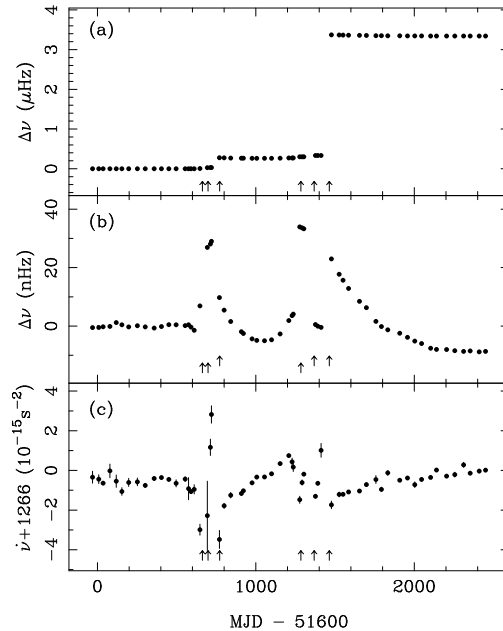


Figure 2. Pulse frequency variations for PSR B1737–30 over an 2500-d period: (a) frequency residual $\Delta\nu$ relative to the pre-glitch solution, (b) an expanded plot of $\Delta\nu$ where the mean residual between glitches with a raised arrow and the following glitch has been removed from data after the marked glitch, and (c) the variations of $\dot{\nu}$.

d) data span gives a good fit to the data. However, the derived value of $\Delta\dot{\nu}_p$ is highly covariant with the exponential decay term; for the solution given in Table 2 we have fixed the decay timescale at 100 d.

The two largest glitches observed are the third glitch (MJD 52347.66) and the final glitch (MJD 53036). Both are the final glitch of their group. Following the short-term (50 – 100 d) exponential recovery, Fig. 2 shows that, for these two glitches, there is an approximately linear increase in $\dot{\nu}$ until the next glitch. The slopes of these two linear regions are not the same, with the earlier one having a gradient about four times as large, despite it being the smaller glitch.

As we were completing this work, Janssen & Stappers (2006) published glitch parameters on seven pulsars that include PSR B1737–30. Within the data span covered by the Nanshan observations they report a total of 10 glitches. The first three of those glitches (between MJD 51685 and 52007) have $\Delta\nu/\nu < 10^{-9}$. Our data do not show any significant jumps (above the level of timing noise) in this interval. Such glitch magnitudes imply residual slopes of ~ 1 ms in 20 days. Our fit to the 700-d data span (MJD 51549 – 52232; Table 1) has an rms residual of ~ 1 ms and there is no evidence for discontinuities in the pulse phase. The paper also reports two other small glitches, with $\Delta\nu/\nu \sim 1.5 \times 10^{-9}$ around MJD 52603 and 52759. Similarly, we find no evidence for discontinuities at these times (see residual plot for glitch 4 in Fig. 1, Fig. 2 and Table 1). For three of the five significant glitches (with $\Delta\nu/\nu > 10^{-9}$) in Janssen & Stappers (2006), we obtain glitch magnitudes that disagree substantially with the values given in that paper, ours being generally lower. In two of the three cases (glitches 1 and 2 in this paper), they differ by an order of magnitude or more, while the glitch epochs are in good agreement. For glitches 4 and 5

Table 1. The rotation parameters for PSR B1737–30. The errors are at 2σ level.

Fit Span (MJD)	Epoch (MJD)	ν (s^{-1})	$\dot{\nu}$ ($10^{-12}s^{-2}$)	$\ddot{\nu}$ ($10^{-24}s^{-3}$)	Residual (μs)	No. of TOAs
51549–52233	51891	1.64806684404(3)	−1.266582(5)	0.6(3)	1012	79
52238–52256	52247	1.6480278954(3)	−1.2688(7)	–	97	4
52287–52339	52313	1.6480206942(2)	−1.2650(3)	–	369	8
52349–52854	52602	1.64798930701(5)	−1.266509(4)	47(1)	1223	51
52860–52923	52892	1.6479576154(1)	−1.2666(1)	–	137	6
52959–53023	52991	1.64794681727(8)	−1.26667(9)	–	147	8
53050–54094	53572	1.64788626572(4)	−1.266449(2)	15.1(2)	2722	103

Table 2. The glitch parameters of PSR B1737–30. The errors are at 2σ level.

Glitch No.	Glitch epoch (MJD)	Date	Fit Span (MJD)	$\Delta\nu_g/\nu$ (10^{-9})	$\Delta\dot{\nu}_g/\dot{\nu}$ (10^{-3})	τ_d (days)	Q	$\Delta\dot{\nu}_g/\dot{\nu}$ (10^{-3})	Residual (μs)
(1)	52237(1)	011111	52005–52256	5.0(4)	–	–	–	–	353
(2)	52260(4)	011217	52238–52339	12(4)	−3(3)	–	–	−3(3)	311
(3)	52347.66(6)	020314	52287–52450	152(2)	−4.6(4)	50	0.103(9)	0.1(7)	297
(4)	52858(2)	030807	52367–52923	19(2)	1.0(6)	–	–	1.0(6)	1020
(5)	52941.3(6)	031029	52860–53063	21.6(6)	0.4(2)	–	–	0.4(2)	219
(6)	53036(13)	040201	52965–53218	1853.6(14)	−5.36(7)	100	0.0302(6)	3.0(2)	256

of this paper, the glitch magnitudes and epochs are in good agreement with the Janssen & Stappers (2006) values. Our glitch 6 is outside their data span. The differing results are probably a result of sparse sampling in their early data (G. Janssen, private communication).

4 DISCUSSION

PSR B1737–30 is one of the most frequently glitching pulsars, and it has a large range of glitch amplitudes. Table 3 presents the 14 glitches of PSR B1737–30 previously published by McKenna & Lyne (1990), Shemar & Lyne (1996) and Krawczyk et al. (2003). Adding the six glitches given in Table 3 brings the total to 20 glitches in the 20 years 1986 to 2006. The glitch history of $\Delta\nu/\nu$ for the 20 glitches is shown in Fig. 3. Unlike PSR J0537–6910 (Middleditch et al. 2006), there is no clear relationship of interval to the next glitch to glitch size. In PSR B1737–30, the glitches tend to cluster in groups. Sometimes the last glitch of a group is small (e.g., the group between MJD 49000 and 49600) and sometimes it is large (e.g., glitch 6 at MJD 53035).

For the Vela pulsar and some others, e.g. PSR B1800–21 (see the table of glitches in the ATNF Pulsar Catalogue), the glitches are either large ($\Delta\nu_g/\nu \gtrsim 10^{-6}$) or small ($\Delta\nu_g/\nu \lesssim 10^{-8}$). PSR J0537–6910 is similar except that the typical large glitch is smaller, $\Delta\nu_g/\nu \sim 3 \times 10^{-7}$. However, in common with a number of other pulsars, e.g., PSRs B1046–58 and PSR B1338–62, PSR B1737–30 has a more uniform distribution of glitch sizes. Excepting PSR J0537–6910 which is younger, all of these pulsars have characteristic ages in the range $1 - 2 \times 10^4$ years, so the apparent difference in glitch properties is not simply a function of (characteristic) age. The difference appears quite significant, but its origin is unclear.

Derived values of $\Delta\dot{\nu}_g/\dot{\nu}$ are much less reliable since they depend heavily on the post-glitch sampling and the

Table 3. Published glitches of PSR B1737–30.

Epoch MJD	$\Delta\nu_g/\nu$ (10^{-9})	$\Delta\dot{\nu}_g/\dot{\nu}$ (10^{-3})	Refs
47003(25)	420(20)	3(1)	1
47281(2)	33(5)	2(4)	1
47332(16)	7(5)	−1(12)	1
47458(2)	30(8)	0(4)	1
47670.2(2)	600.9(6)	2.0(4)	1
48186(6)	642(16)	−5(12)	2
48218(2)	48(10)	8(12)	2
48431(1)	15.7(5)	0.8(3)	2
49046(4)	10.0(4)	0.01(6)	2
49239(2)	169.6(3)	0.8(1)	2
49451.7(4)	9.5(5)	−0.32(2)	3
49543.93(8)	3.0(6)	−0.68(2)	3
50574.5497(4)	439.3(2)	1.261(2)	3
50941.6182(2)	1443.0(3)	1.231(5)	3

References: 1. McKenna & Lyne (1990); 2. Shemar & Lyne (1996); 3. Krawczyk et al. (2003).

adequacy of the model for the post-glitch decay. Earlier values are quite uncertain, but for most of the larger glitches $\Delta\dot{\nu}_g/\dot{\nu} \sim 10^{-3}$, about an order of magnitude less than the corresponding values for the Vela pulsar. The linear increases in $\dot{\nu}$ in the intervals following the two large glitches at MJD 52347 and 53036 are qualitatively similar to those observed in the Vela pulsar (Lyne et al. 1996). However, the linear gradients observed in Vela are much steeper, typically $\sim 25 \times 10^{-15} s^{-2} yr^{-1}$ whereas, for PSR B1737–30, even the steeper gradient following the glitch of MJD 52347 is just $\sim 2 \times 10^{-15} s^{-2} yr^{-1}$.

The glitch activity, A_g , defined as the mean fractional change in period per year owing to glitches (McKenna & Lyne 1990), is given by the simple expression:

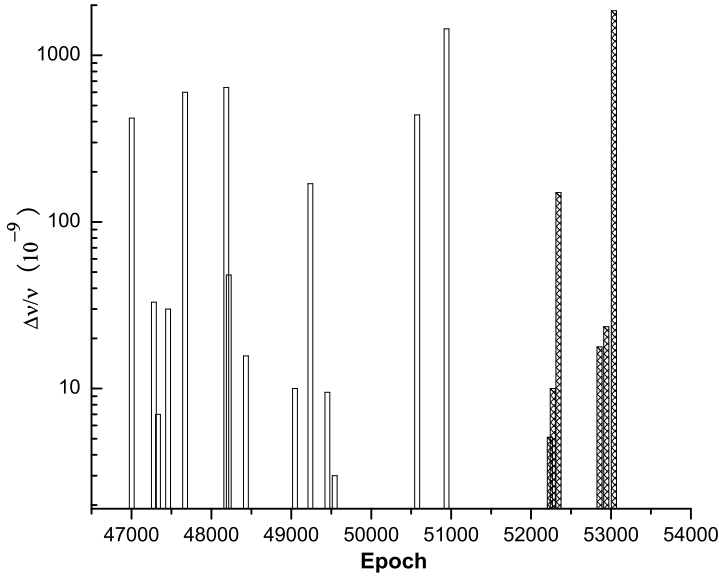


Figure 3. The glitch history of PSR B1737–30. Glitches from MJD 52000 are from our work.

$$A_g = \frac{1}{t_g} \sum \frac{\Delta\nu_g}{\nu}, \quad (4)$$

where $\sum \Delta\nu_g/\nu$ is the total fractional increase of frequency owing to all of the glitches over an interval of t_g . PSR B1737–30 has a relatively high glitch activity with $A_g = 2.96 \times 10^{-7} \text{ yr}^{-1}$. An advantage of A_g as a long-term indicator of glitch effects is that it is relatively insensitive to the additional discovery of smaller glitches as the data quality improves (Wong et al. 2001). Pulsars can be grouped into three classes: pulsars with low glitch activity (e.g., PSR B0525+21), high glitch activity (e.g., Vela pulsar) and no glitch activity. PSR B1737–30 belongs among those with high glitch activity. The pulsars with characteristic ages between 10^4 and 10^5 yr are more likely to have higher glitch activity than the younger ones ($\tau_c < 10^4$ yr) or the older ones ($\tau_c > 10^5$ yr) as shown by statistical studies of pulsar glitches (Urama & Okeke 1999; Lyne et al. 2000; Wang et al. 2000).

Fig. 4 shows the evolution of the spin frequency ν and the slow-down rate $\dot{\nu}$ over 20 years. Clearly, the long-term evolution of ν is dominated by the regular spin-down – the glitches are not even visible on this plot. The lower part of Fig. 4 shows that there has been a long-term decrease in $\dot{\nu}$ (increase in $|\dot{\nu}|$) of about $\sim 0.1\%$ over the 20 years. This corresponds to a value of $\ddot{\nu} \sim -3 \times 10^{-24} \text{ s}^{-3}$. The braking index is therefore -3 ± 1 for the long-term evolution of PSR B1737–30. Inter-glitch data spans are frequently affected by relaxation from large glitches and generally have large positive braking indices (Johnston & Galloway 1999; Wang et al. 2001). For example, we obtain a braking index of $n = 13 \pm 1$ by fitting the data starting 500 days after the last glitch (MJD 53550 – 54095).

As mentioned in the Introduction, a negative long-term braking index is also observed for PSR J0537–6910 (Middleditch et al. 2006). Permanent increases in $|\dot{\nu}|$ associated with glitches are also observed in the Crab pulsar (Lyne et al. 2000; Wong et al. 2001). In this case though, since the glitches are much smaller, they do not bias the observed braking index so much. The Vela pul-

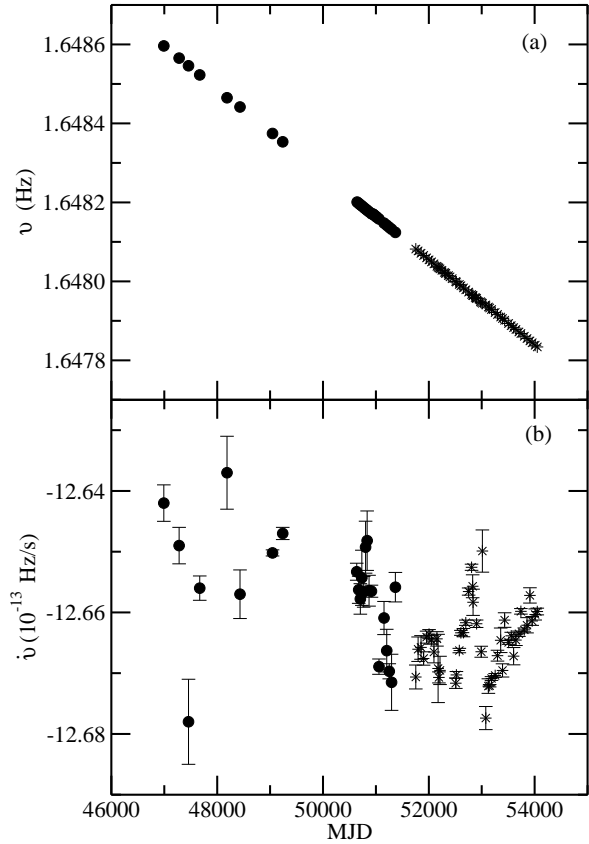


Figure 4. Evolution of the spin parameters over 20 years (a) rotation frequency ν , and (b) spin-down rate, $\dot{\nu}$. Points marked with a \bullet are from Shemar & Lyne (1996); Urama (2002) and Krawczyk et al. (2003); those with a $*$ from the present work. We have omitted the measured $\dot{\nu}$ values < 150 days after a glitch.

sar also has an anomalously low value of n (Lyne et al. 1996) which may be likewise related to the frequent glitches. A possible interpretation of these observations is that the component of the magnetic dipole moment which is perpendicular to the spin axis increases at the time of a glitch (Link, Franco & Epstein 1998; Ruderman Zhu & Chen 1998).

Fig. 4(b) also shows what appears to be a cyclic variation in $\dot{\nu}$ superimposed over the linear trend. Such a cyclic variation would have ~ 3000 d period and needs at least another cycle to confirm.

Fig. 5 is a plot of pulsar period P versus period derivative \dot{P} of all known 1700 pulsars which distinguishes the glitching pulsars and other different classes of pulsars. The most frequently glitching pulsars are young and have relatively strong dipole fields. Some glitching pulsars are older, including PSR B1821–24, which is a recycled pulsar in the globular cluster M28 (Cognard & Backer 2004). At present, 20 pulsars have detected giant glitches and, except PSR B2224+65 whose age is 1.12×10^6 yr, all the pulsars which have giant glitches are in the younger group.

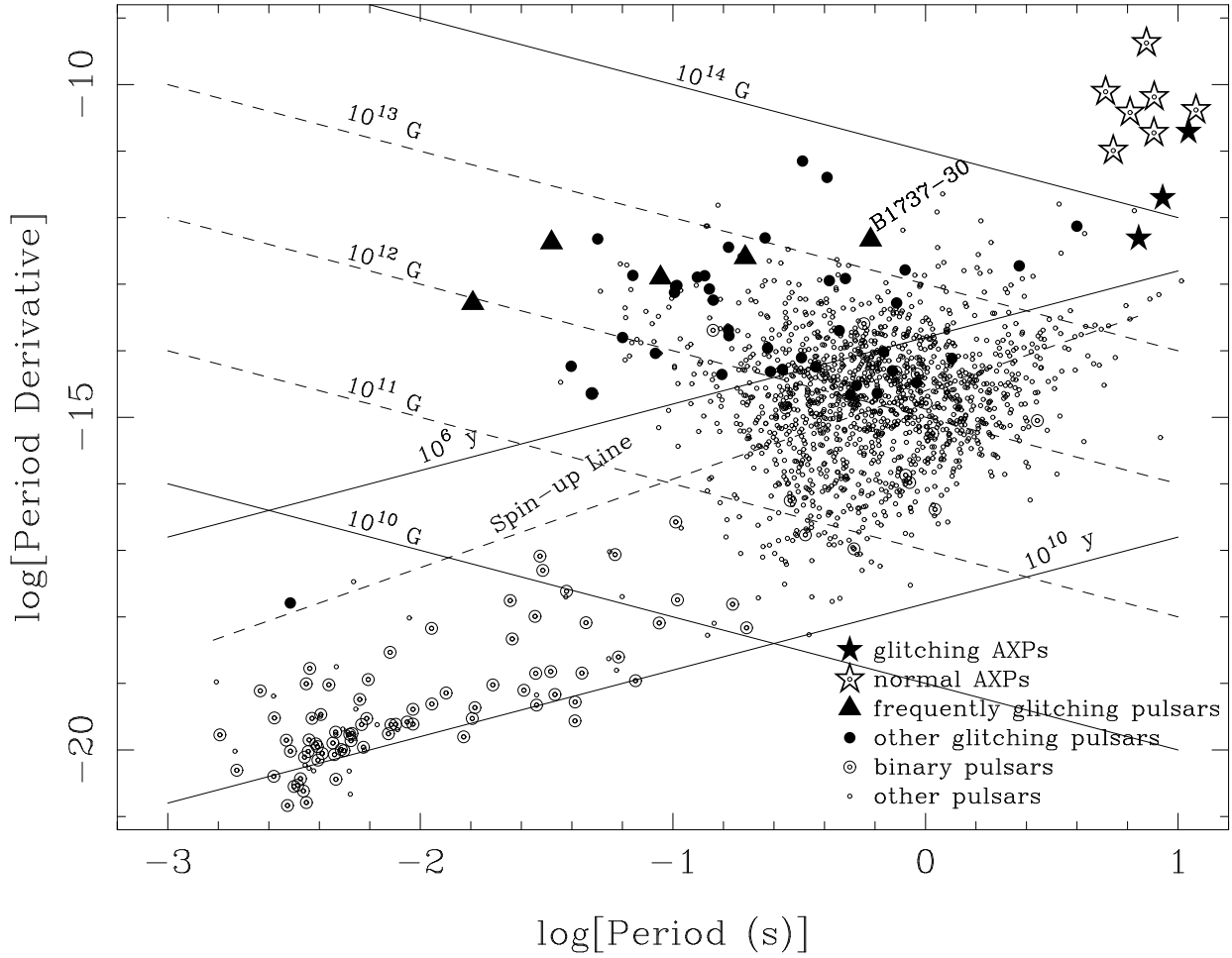


Figure 5. Distribution of known pulsars in the period — period-derivative plane. Glitching AXPs are shown by filled stars, frequently glitching pulsars are indicated by triangles and the rest of the glitching pulsars are marked by bold points. Lines of constant characteristic age and surface dipole magnetic field strength are shown.

5 CONCLUSIONS

Our observations of PSR B1737–30 show six glitches in PSR B1737–30 over a period of seven years. In total, 20 glitches have been observed over a 20-year period. Glitch sizes cover a wide range from just a few parts in 10^9 to large glitches comparable to those seen in the Vela pulsar. The inter-glitch intervals are highly variable, ranging from 3 weeks to more than 3 years. Unlike in PSR J0537–6910, there is no clear relationship of glitch interval with size of the preceding glitch. Although the age of PSR B1737–30 is comparable to that of the Vela pulsar, their glitch behaviours are different, with glitch sizes and intervals being much more variable in PSR B1737–30. Exponential and quasi-linear relaxations in $\dot{\nu}$ are observed in both pulsars, but with quite different parameters. It is remarkable that the three most highly glitching pulsars have such different glitch and post-glitch properties, yet another example of the diversity and complexity of magnetised neutron stars.

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Observations of Six Glitches in PSR B1737–30

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ABSTRACT

Six glitches have been recently observed in the rotational frequency of the young pulsar PSR B1737–30 (J1740–3015) using the 25-m Nanshan telescope of Urumqi Observatory. With a total of 20 glitches in 20 years, it is one of the most frequently glitching pulsars of the ~ 1750 known pulsars. Glitch amplitudes are very variable with fractional increases in rotation rate ranging from 10^{-9} to 10^{-6} . Inter-glitch intervals are also very variable, but no relationship is observed between interval and the size of the preceding glitch. There is a persistent increase in $|\dot{\nu}|$, opposite in sign to that expected from slowdown with a positive braking index, which may result from changes in the effective magnetic dipole moment of the star during the glitch.

Key words: stars: neutron – pulsars: individual: PSR B1737–30

1 INTRODUCTION

Glitches in pulsars are rare and extraordinary events. The study of such glitches and their post-glitch recoveries can give an insight into the interior of neutron stars, the physics of ultradense matter and provide limits on the equation of state (Pines 1991; Alpar et al. 1993; Franco et al. 2000). Pulsar glitches are usually detected from long-term and frequent timing observations. The number of observed glitches has increased dramatically in the past few years, which probably is due to both the increased continuous observations of active pulsars and a large number of new young pulsars detected by the pulsar surveys (e.g., the Parkes surveys, see Kramer et al. 2003) over the last decade.

Glitches are characterized as sudden increases in the rotation frequency $\nu = 1/P$ (where P is the pulsar period), often followed by an interval of approximately exponential recovery or relaxation back towards the pre-glitch frequency. The post-glitch relaxation can have timescale of days to years. Frequency jumps with magnitudes $\Delta\nu/\nu \sim 10^{-6}$ are recognized as “giant” glitches, and have been observed mostly in pulsars with characteristic ages $\tau_c = P/(2\dot{P}) \sim 10^4$ yr, such as PSRs B0833–45 (the Vela pulsar), B1046–58 and B1338–62 (Wang et al. 2000). Giant glitches have not been observed in the youngest radio pulsars, such as PSR B0531+21 (the Crab pulsar) and

PSR B1509–58. Detected glitches are generally of magnitude $10^{-9} < \Delta\nu/\nu < 10^{-6}$, and the relative increment in slow-down rate $\Delta\dot{\nu}/\dot{\nu}$ is in the range 10^{-3} to 10^{-2} . Very small glitches with $\Delta\nu/\nu < 10^{-9}$ are difficult to distinguish from timing noise in young pulsars (Hobbs et al. 2002). Of the 1750 known pulsars, about 170 glitches in 54 pulsars have been observed so far¹. Half of the published glitches have fractional amplitudes $\Delta\nu/\nu \sim 10^{-8}$. Most glitches detected in the Vela pulsar are giant glitches, and the largest glitch, with $\Delta\nu/\nu \approx 16 \times 10^{-6}$, was observed in PSR J1806–2125 (Hobbs et al. 2002). About 60% of the 54 glitching pulsars have glitched only once, and 16% have glitched twice. Observations with Rossi X-ray Timing Explorer (RXTE) have revealed that PSR J0537–6910, the 16-ms pulsar associated with the supernova remnant N157B in the Large Magellanic Cloud, is the most frequently glitching known pulsar with 23 glitches detected in seven years of monitoring (Middleditch et al. 2006). Most of the glitches have $\Delta\nu/\nu$ of a few $\times 10^{-7}$ and, interestingly, a strong correlation is observed between the amplitude of a glitch and the time to the next one. Furthermore, despite the usual post-glitch recovery (decrease) in $|\dot{\nu}|$, a persistent long-term increase in this parameter is observed, corresponding to a negative braking index $n = \nu\ddot{\nu}/\dot{\nu}^2 \sim -1.5$. This increase is

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¹ See <http://www.atnf.csiro.au/research/pulsar/psrcat/> and Manchester et al. (2005)

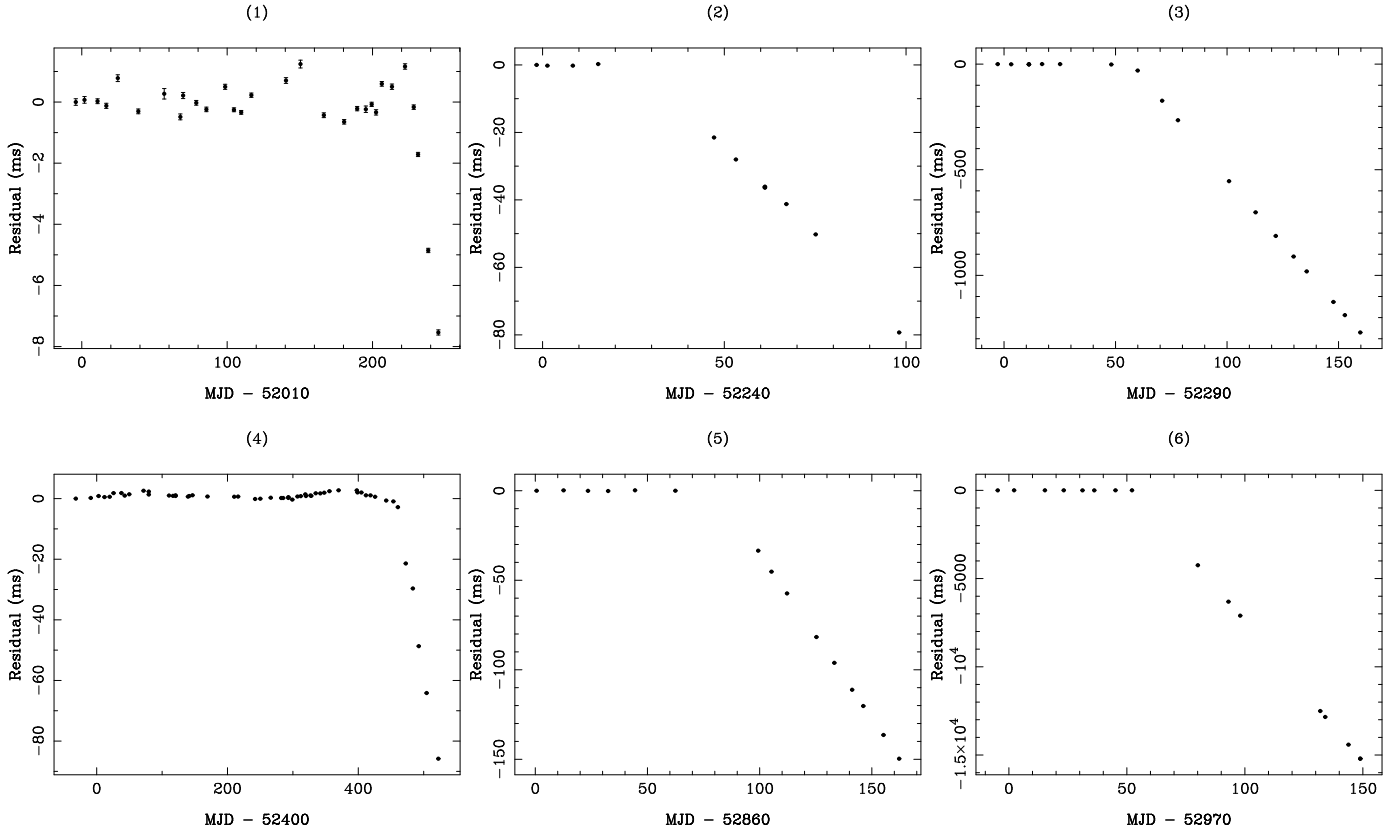


Figure 1. Timing residuals relative to the pre-glitch timing model for six glitches in the rotation history of PSR B1737–30. Residuals are defined in the sense of observed arrival time minus predicted arrival time.

most probably related to changes on or in the neutron star that result from the glitch activity.

In this paper we report on six recent glitches detected in the period of PSR B1737–30 and discuss the implications of these results. PSR B1737–30 is a young radio pulsar with a characteristic age of 2.06×10^4 yr which glitches frequently, with 20 glitches of all sizes ranging from “small” to “giant” ($\Delta\nu/\nu \sim 10^{-9}$ to 10^{-6}) observed since its discovery in 1986 (McKenna & Lyne 1990; Shemar & Lyne 1996; Krawczyk et al. 2003, this paper). As for PSR J0537–6910, there appears to be a cumulative shift in the spin-down rate of PSR B1737–30 resulting from its frequent glitches, which most likely accounts for its long-term braking index of $n = -4 \pm 2$ (Urama 2002).

2 OBSERVATIONS AND ANALYSIS

The timing observations of PSR B1737–30 using the 25-m Nanshan radio telescope of Urumqi Observatory started in 2000 January using a room-temperature dual-channel receiver. From 2002 July a dual-channel cryogenic receiver system sensitive to two orthogonal polarizations was used at a central observing frequency of 1540 MHz. Two polarizations, each of bandwidth 320 MHz, are fed to a filterbank consisting of 2×128 channels of width 2.5 MHz. The data are digitized to one-bit precision with a sampling interval of 1 ms. Time is provided by a hydrogen maser clock calibrated using the Global Positioning System. Observations times for PSR B1737–30 were generally 16 min with the room-temperature

receiver before 2002 July and 4 min with the cryogenic receiver after that date.

The data are dedispersed with off-line programs to remove the effects of interstellar dispersion, and then folded at the pulsar’s nominal topocentric period with four sub-integrations per observation. The pulse profiles obtained by summing an observation were cross-correlated with a high signal-to-noise template of the pulsar profile to produce accurate pulse topocentric times of arrival (TOAs), which are then processed with the standard timing program TEMPO² to convert them to barycentric arrival times at infinite frequency. The TOAs refer to the peak of the main pulse. The Jet Propulsion Laboratory ephemeris DE405 is used to correct the TOAs to the Solar system barycenter. The folded profiles are stored on disk for subsequent processing and analysis. Timing observations are usually made approximately three times per month and the glitching pulsars are observed more frequently.

We use the corrected barycentric TOAs to determine the basic parameters of the pulsar. The basic timing model gives the predicted rotational pulse phase $\phi_m(t)$, as a function of time, t :

$$\phi_m(t) = \phi_0 + \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}_0(t - t_0)^2 + \frac{1}{6}\ddot{\nu}_0(t - t_0)^3. \quad (1)$$

Timing irregularities appear as phase residuals ($\phi - \phi_m$), which are usually divided by ν to place them in time units.

² see <http://www.atnf.csiro.au/research/pulsar/tempo/>

For a glitching pulsar the residuals suddenly develop a negative slope at the time of the glitch as illustrated in Fig. 1. The frequency perturbation due to the glitch can usually be described by:

$$\Delta\nu(t) = \Delta\nu_p + \Delta\dot{\nu}_p t + \Delta\nu_d \exp(-t/\tau_d), \quad (2)$$

where $\Delta\nu = \nu - \nu_0$ is the change in pulse frequency relative to the pre-glitch model, $\Delta\nu_p$ and $\Delta\dot{\nu}_p$ are the permanent changes in frequency and frequency derivative respectively and $\Delta\nu_d$ is the amplitude of the exponential recovery with a decay time constant of τ_d . The total frequency jump at the time of the glitch $\Delta\nu_g = \Delta\nu_p + \Delta\nu_d$ and the degree of recovery is often described by the parameter $Q = \Delta\nu_d/\Delta\nu_g$. Because of the decaying component, the instantaneous change in $\dot{\nu}$ at the glitch differs from $\Delta\dot{\nu}_p$:

$$\Delta\dot{\nu}_g = \Delta\dot{\nu}_p - Q\Delta\nu_g/\tau_d. \quad (3)$$

The glitch model of Equation 2 describes the post-glitch behaviour fairly well for most glitches (Shemar & Lyne 1996; Wang et al. 2000).

3 RESULTS

Six glitches have been observed in the period of PSR B1737–30 over the seven-year monitoring period from 2000 January 6 (MJD 51549) to 2006 December 25 (MJD 54094). The rotation history of these glitches with respect to pre-glitch timing models are shown in Fig. 1. No glitches have been observed since 2004 February, i.e., for nearly three years. Tables 1 and 2 give the main parameters of the six glitches. Uncertainties are parentheses and refer to the last quoted digit. Glitch parameters have been determined by fitting Equation 2 to the timing data around each glitch. For the smaller glitches, the glitch epoch is determined unambiguously by the requirement of pulse phase continuity. The last large glitch, the epoch is ambiguous and is given as the mean of the dates of the last pre-glitch and the first post-glitch observations. Except for the largest glitch, the magnitudes of these glitches are comparable to those observed from Crab pulsar ($\sim 10^{-8}$), but generally 2–3 orders smaller than the typical glitch of the Vela pulsar ($\Delta\nu/\nu \sim 10^{-6}$). No changes associated with the glitches in the pulse shape or flux density have been observed.

Fig. 2 shows the time-evolution of the residual frequency ($\Delta\nu$) and the frequency first derivative ($\dot{\nu}$) over a 2500-d period. The six glitches are clustered in two groups of three. The first observed glitch, at epoch MJD 52237 (2001 November 11, glitch 1 in Fig. 1) is very small, with a fractional change in the rotation rate $\Delta\nu_g/\nu \sim 5 \times 10^{-9}$. A relatively large glitch ($\Delta\nu_g/\nu \sim 1.52 \times 10^{-7}$) occurred at epoch MJD 52347.66 (2002 March 14, glitch 3 in Fig. 1), the amplitude of which is similar to a typical glitch of PSR B1758–23; PSRs B1737–30 and B1758–23 have similar properties — age, period, period derivative and spin-down energy loss rate. The relaxation after this glitch is adequately modelled by an exponential decay of time scale ~ 50 d with $Q \sim 0.1$. The largest glitch so far observed in this pulsar with $\Delta\nu/\nu = 1.85 \times 10^{-6}$ occurred on MJD 53036 ± 13 (2004 February 1, glitch 6 in Fig. 1). This is a Vela-type glitch. Fitting glitch parameters to a relatively short (200

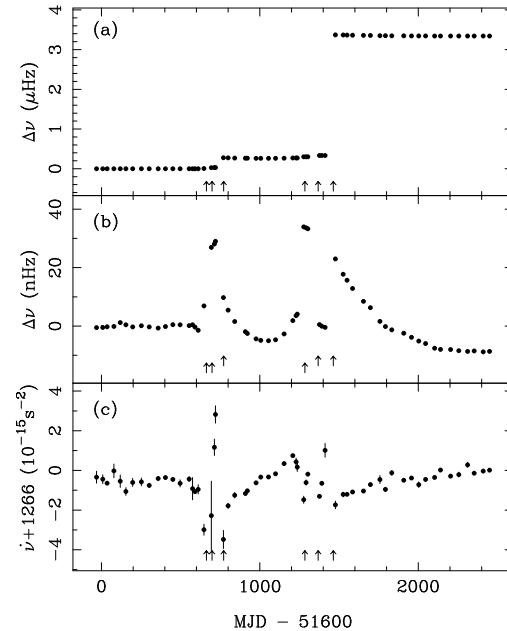


Figure 2. Pulse frequency variations for PSR B1737–30 over an 2500-d period: (a) frequency residual $\Delta\nu$ relative to the pre-glitch solution, (b) an expanded plot of $\Delta\nu$ where the mean residual between glitches with a raised arrow and the following glitch has been removed from data after the marked glitch, and (c) the variations of $\dot{\nu}$.

d) data span gives a good fit to the data. However, the derived value of $\Delta\dot{\nu}_p$ is highly covariant with the exponential decay term; for the solution given in Table 2 we have fixed the decay timescale at 100 d.

The two largest glitches observed are the third glitch (MJD 52347.66) and the final glitch (MJD 53036). Both are the final glitch of their group. Following the short-term (50 – 100 d) exponential recovery, Fig. 2 shows that, for these two glitches, there is an approximately linear increase in $\dot{\nu}$ until the next glitch. The slopes of these two linear regions are not the same, with the earlier one having a gradient about four times as large, despite it being the smaller glitch.

As we were completing this work, Janssen & Stappers (2006) published glitch parameters on seven pulsars that include PSR B1737–30. Within the data span covered by the Nanshan observations they report a total of 10 glitches. The first three of those glitches (between MJD 51685 and 52007) have $\Delta\nu/\nu < 10^{-9}$. Our data do not show any significant jumps (above the level of timing noise) in this interval. Such glitch magnitudes imply residual slopes of ~ 1 ms in 20 days. Our fit to the 700-d data span (MJD 51549 – 52232; Table 1) has an rms residual of ~ 1 ms and there is no evidence for discontinuities in the pulse phase. The paper also reports two other small glitches, with $\Delta\nu/\nu \sim 1.5 \times 10^{-9}$ around MJD 52603 and 52759. Similarly, we find no evidence for discontinuities at these times (see residual plot for glitch 4 in Fig. 1, Fig. 2 and Table 1). For three of the five significant glitches (with $\Delta\nu/\nu > 10^{-9}$) in Janssen & Stappers (2006), we obtain glitch magnitudes that disagree substantially with the values given in that paper, ours being generally lower. In two of the three cases (glitches 1 and 2 in this paper), they differ by an order of magnitude or more, while the glitch epochs are in good agreement. For glitches 4 and 5

Table 1. The rotation parameters for PSR B1737–30. The errors are at 2σ level.

Fit Span (MJD)	Epoch (MJD)	ν (s^{-1})	$\dot{\nu}$ ($10^{-12}s^{-2}$)	$\ddot{\nu}$ ($10^{-24}s^{-3}$)	Residual (μs)	No. of TOAs
51549–52233	51891	1.64806684404(3)	–1.266582(5)	0.6(3)	1012	79
52238–52256	52247	1.6480278954(3)	–1.2688(7)	–	97	4
52287–52339	52313	1.6480206942(2)	–1.2650(3)	–	369	8
52349–52854	52602	1.64798930701(5)	–1.266509(4)	47(1)	1223	51
52860–52923	52892	1.6479576154(1)	–1.2666(1)	–	137	6
52959–53023	52991	1.64794681727(8)	–1.26667(9)	–	147	8
53050–54094	53572	1.64788626572(4)	–1.266449(2)	15.1(2)	2722	103

Table 2. The glitch parameters of PSR B1737–30. The errors are at 2σ level.

Glitch No.	Glitch epoch (MJD)	Date	Fit Span (MJD)	$\Delta\nu_g/\nu$ (10^{-9})	$\Delta\dot{\nu}_g/\dot{\nu}$ (10^{-3})	τ_d (days)	Q	$\Delta\dot{\nu}_g/\dot{\nu}$ (10^{-3})	Residual (μs)
(1)	52237(1)	011111	52005–52256	5.0(4)	–	–	–	–	353
(2)	52260(4)	011217	52238–52339	12(4)	–3(3)	–	–	–3(3)	311
(3)	52347.66(6)	020314	52287–52450	152(2)	–4.6(4)	50	0.103(9)	0.1(7)	297
(4)	52858(2)	030807	52367–52923	19(2)	1.0(6)	–	–	1.0(6)	1020
(5)	52941.3(6)	031029	52860–53063	21.6(6)	0.4(2)	–	–	0.4(2)	219
(6)	53036(13)	040201	52965–53218	1853.6(14)	–5.36(7)	100	0.0302(6)	3.0(2)	256

of this paper, the glitch magnitudes and epochs are in good agreement with the Janssen & Stappers (2006) values. Our glitch 6 is outside their data span. The differing results are probably a result of sparse sampling in their early data (G. Janssen, private communication).

4 DISCUSSION

PSR B1737–30 is one of the most frequently glitching pulsars, and it has a large range of glitch amplitudes. Table 3 presents the 14 glitches of PSR B1737–30 previously published by McKenna & Lyne (1990), Shemar & Lyne (1996) and Krawczyk et al. (2003). Adding the six glitches given in Table 3 brings the total to 20 glitches in the 20 years 1986 to 2006. The glitch history of $\Delta\nu/\nu$ for the 20 glitches is shown in Fig. 3. Unlike PSR J0537–6910 (Middleditch et al. 2006), there is no clear relationship of interval to the next glitch to glitch size. In PSR B1737–30, the glitches tend to cluster in groups. Sometimes the last glitch of a group is small (e.g., the group between MJD 49000 and 49600) and sometimes it is large (e.g., glitch 6 at MJD 53035).

For the Vela pulsar and some others, e.g. PSR B1800–21 (see the table of glitches in the ATNF Pulsar Catalogue), the glitches are either large ($\Delta\nu_g/\nu \gtrsim 10^{-6}$) or small ($\Delta\nu_g/\nu \lesssim 10^{-8}$). PSR J0537–6910 is similar except that the typical large glitch is smaller, $\Delta\nu_g/\nu \sim 3 \times 10^{-7}$. However, in common with a number of other pulsars, e.g., PSRs B1046–58 and PSR B1338–62, PSR B1737–30 has a more uniform distribution of glitch sizes. Excepting PSR J0537–6910 which is younger, all of these pulsars have characteristic ages in the range $1 - 2 \times 10^4$ years, so the apparent difference in glitch properties is not simply a function of (characteristic) age. The difference appears quite significant, but its origin is unclear.

Derived values of $\Delta\dot{\nu}_g/\dot{\nu}$ are much less reliable since they depend heavily on the post-glitch sampling and the

Table 3. Published glitches of PSR B1737–30.

Epoch MJD	$\Delta\nu_g/\nu$ (10^{-9})	$\Delta\dot{\nu}_g/\dot{\nu}$ (10^{-3})	Refs
47003(25)	420(20)	3(1)	1
47281(2)	33(5)	2(4)	1
47332(16)	7(5)	–1(12)	1
47458(2)	30(8)	0(4)	1
47670.2(2)	600.9(6)	2.0(4)	1
48186(6)	642(16)	–5(12)	2
48218(2)	48(10)	8(12)	2
48431(1)	15.7(5)	0.8(3)	2
49046(4)	10.0(4)	0.01(6)	2
49239(2)	169.6(3)	0.8(1)	2
49451.7(4)	9.5(5)	–0.32(2)	3
49543.93(8)	3.0(6)	–0.68(2)	3
50574.5497(4)	439.3(2)	1.261(2)	3
50941.6182(2)	1443.0(3)	1.231(5)	3

References: 1. McKenna & Lyne (1990); 2. Shemar & Lyne (1996); 3. Krawczyk et al. (2003).

adequacy of the model for the post-glitch decay. Earlier values are quite uncertain, but for most of the larger glitches $\Delta\dot{\nu}_g/\dot{\nu} \sim 10^{-3}$, about an order of magnitude less than the corresponding values for the Vela pulsar. The linear increases in $\dot{\nu}$ in the intervals following the two large glitches at MJD 52347 and 53036 are qualitatively similar to those observed in the Vela pulsar (Lyne et al. 1996). However, the linear gradients observed in Vela are much steeper, typically $\sim 25 \times 10^{-15} s^{-2} yr^{-1}$ whereas, for PSR B1737–30, even the steeper gradient following the glitch of MJD 52347 is just $\sim 2 \times 10^{-15} s^{-2} yr^{-1}$.

The glitch activity, A_g , defined as the mean fractional change in period per year owing to glitches (McKenna & Lyne 1990), is given by the simple expression:

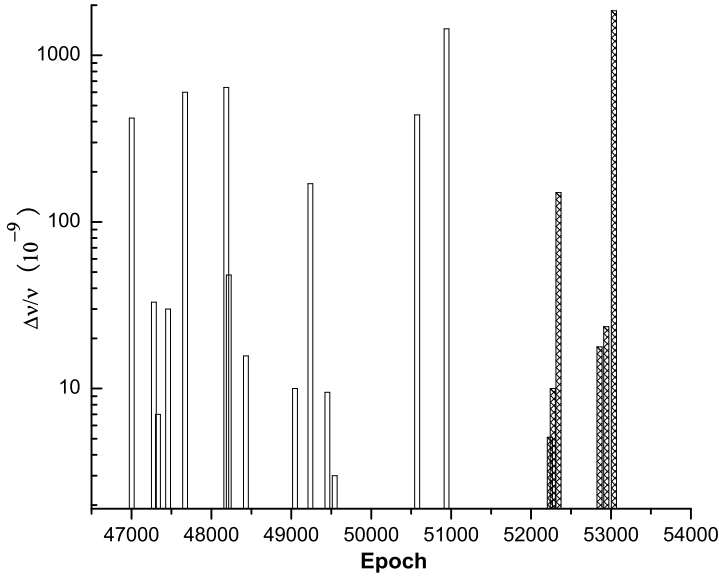


Figure 3. The glitch history of PSR B1737–30. Glitches from MJD 52000 are from our work.

$$A_g = \frac{1}{t_g} \sum \frac{\Delta\nu_g}{\nu}, \quad (4)$$

where $\sum \Delta\nu_g/\nu$ is the total fractional increase of frequency owing to all of the glitches over an interval of t_g . PSR B1737–30 has a relatively high glitch activity with $A_g = 2.96 \times 10^{-7} \text{ yr}^{-1}$. An advantage of A_g as a long-term indicator of glitch effects is that it is relatively insensitive to the additional discovery of smaller glitches as the data quality improves (Wong et al. 2001). Pulsars can be grouped into three classes: pulsars with low glitch activity (e.g., PSR B0525+21), high glitch activity (e.g., Vela pulsar) and no glitch activity. PSR B1737–30 belongs among those with high glitch activity. The pulsars with characteristic ages between 10^4 and 10^5 yr are more likely to have higher glitch activity than the younger ones ($\tau_c < 10^4$ yr) or the older ones ($\tau_c > 10^5$ yr) as shown by statistical studies of pulsar glitches (Urama & Okeke 1999; Lyne et al. 2000; Wang et al. 2000).

Fig. 4 shows the evolution of the spin frequency ν and the slow-down rate $\dot{\nu}$ over 20 years. Clearly, the long-term evolution of ν is dominated by the regular spin-down – the glitches are not even visible on this plot. The lower part of Fig. 4 shows that there has been a long-term decrease in $\dot{\nu}$ (increase in $|\dot{\nu}|$) of about $\sim 0.1\%$ over the 20 years. This corresponds to a value of $\ddot{\nu} \sim -3 \times 10^{-24} \text{ s}^{-3}$. The braking index is therefore -3 ± 1 for the long-term evolution of PSR B1737–30. Inter-glitch data spans are frequently affected by relaxation from large glitches and generally have large positive braking indices (Johnston & Galloway 1999; Wang et al. 2001). For example, we obtain a braking index of $n = 13 \pm 1$ by fitting the data starting 500 days after the last glitch (MJD 53550 – 54095).

As mentioned in the Introduction, a negative long-term braking index is also observed for PSR J0537–6910 (Middleditch et al. 2006). Permanent increases in $|\dot{\nu}|$ associated with glitches are also observed in the Crab pulsar (Lyne et al. 2000; Wong et al. 2001). In this case though, since the glitches are much smaller, they do not bias the observed braking index so much. The Vela pul-

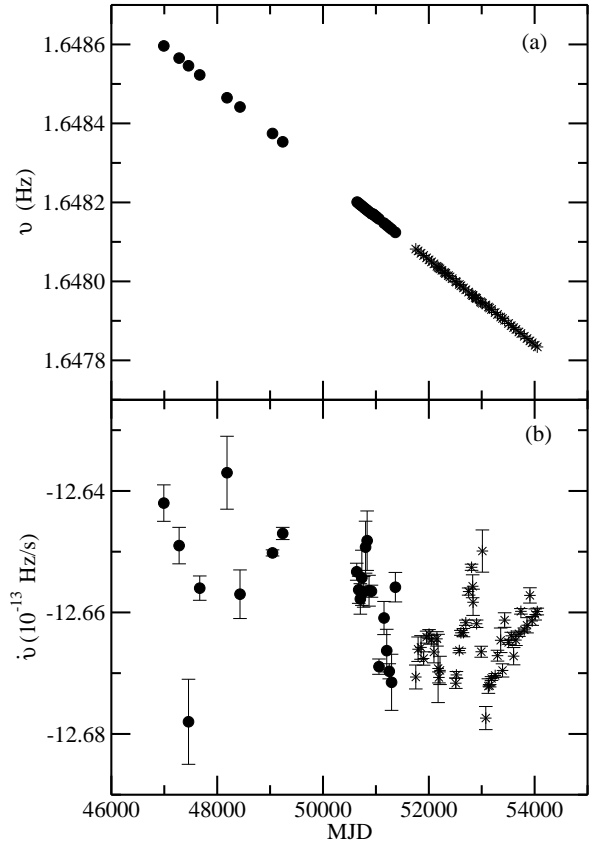


Figure 4. Evolution of the spin parameters over 20 years (a) rotation frequency ν , and (b) spin-down rate, $\dot{\nu}$. Points marked with a \bullet are from Shemar & Lyne (1996); Urama (2002) and Krawczyk et al. (2003); those with a $*$ from the present work. We have omitted the measured $\dot{\nu}$ values < 150 days after a glitch.

sar also has an anomalously low value of n (Lyne et al. 1996) which may be likewise related to the frequent glitches. A possible interpretation of these observations is that the component of the magnetic dipole moment which is perpendicular to the spin axis increases at the time of a glitch (Link, Franco & Epstein 1998; Ruderman Zhu & Chen 1998).

Fig. 4(b) also shows what appears to be a cyclic variation in $\dot{\nu}$ superimposed over the linear trend. Such a cyclic variation would have ~ 3000 d period and needs at least another cycle to confirm.

Fig. 5 is a plot of pulsar period P versus period derivative \dot{P} of all known 1700 pulsars which distinguishes the glitching pulsars and other different classes of pulsars. The most frequently glitching pulsars are young and have relatively strong dipole fields. Some glitching pulsars are older, including PSR B1821–24, which is a recycled pulsar in the globular cluster M28 (Cognard & Backer 2004). At present, 20 pulsars have detected giant glitches and, except PSR B2224+65 whose age is 1.12×10^6 yr, all the pulsars which have giant glitches are in the younger group.

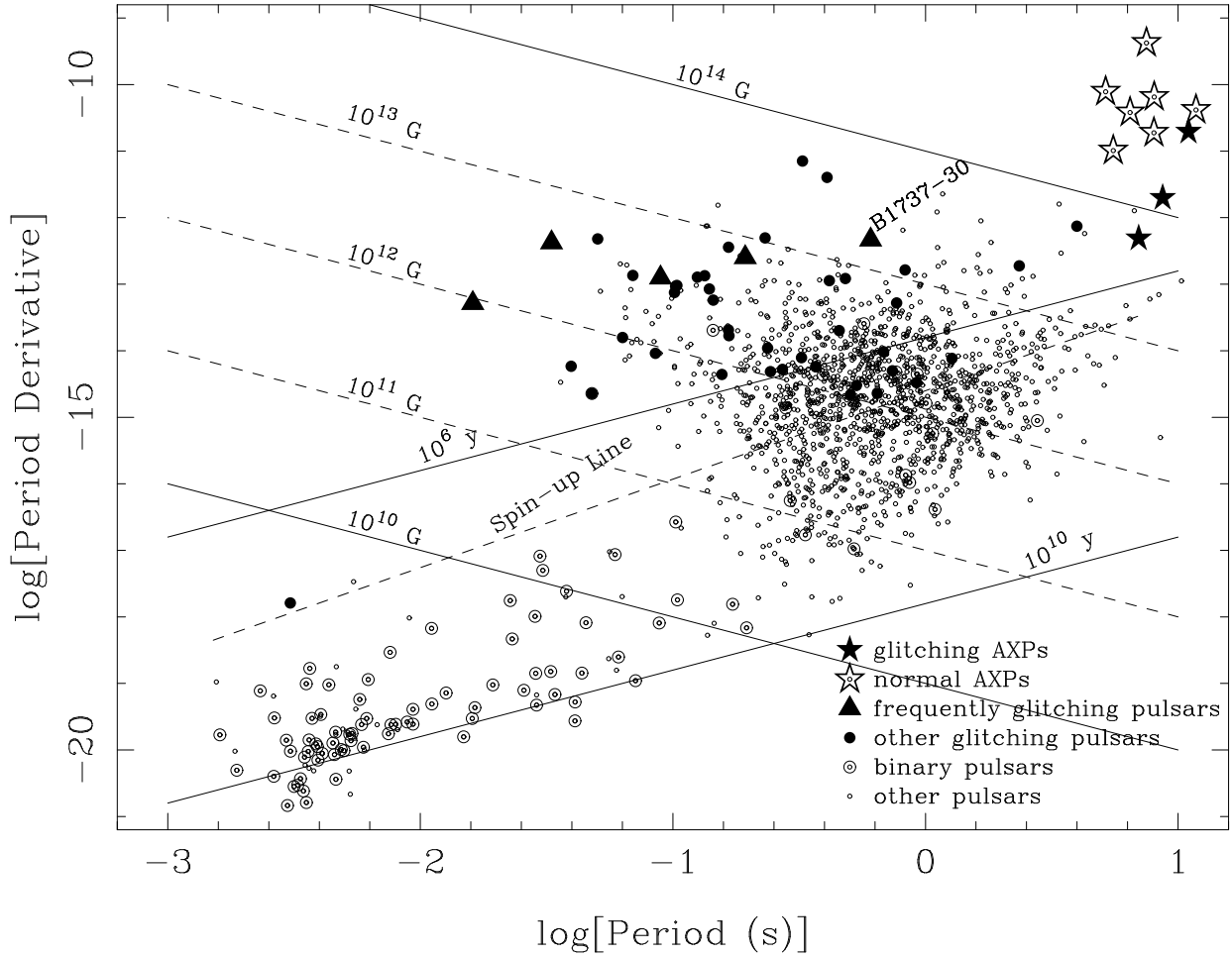


Figure 5. Distribution of known pulsars in the period — period-derivative plane. Glitching AXPs are shown by filled stars, frequently glitching pulsars are indicated by triangles and the rest of the glitching pulsars are marked by bold points. Lines of constant characteristic age and surface dipole magnetic field strength are shown.

5 CONCLUSIONS

Our observations of PSR B1737–30 show six glitches in PSR B1737–30 over a period of seven years. In total, 20 glitches have been observed over a 20-year period. Glitch sizes cover a wide range from just a few parts in 10^9 to large glitches comparable to those seen in the Vela pulsar. The inter-glitch intervals are highly variable, ranging from 3 weeks to more than 3 years. Unlike in PSR J0537–6910, there is no clear relationship of glitch interval with size of the preceding glitch. Although the age of PSR B1737–30 is comparable to that of the Vela pulsar, their glitch behaviours are different, with glitch sizes and intervals being much more variable in PSR B1737–30. Exponential and quasi-linear relaxations in $\dot{\nu}$ are observed in both pulsars, but with quite different parameters. It is remarkable that the three most highly glitching pulsars have such different glitch and post-glitch properties, yet another example of the diversity and complexity of magnetised neutron stars.

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